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METHODS FOR CONTROLLING THERMAL PERFORMANCE OF THE GLASS-MELTING FURNACE

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The specifics and control algorithms of thermal performance of a glass-melting furnace are described. The methods for setting and monitoring the temperature regulation parameters in the working space are analyzed. The results of calculation of the fuel rate, the maximum roof and glass melt temperatures, and their positions along the furnace depending on its output are given. The advantages of using a mathematical model for the construction of an automated control system for the thermal performance of the glass-melting furnace is demonstrated.

The thermal performance of a furnace is understood as a set of heat and mass exchange processes implemented for a prescribed technological process. One of the main conditions of the effective performance of continuous glass-melting furnaces consist in specifying rational regime parameters accepted in glass melting; another condition is ensuring the stability of these parameters. Clearly, to obtain high-quality glass with minimum energy consumption, both conditions have to be satisfied, as they are interrelated and interdependent. The practical implementation of these conditions constitutes the essence of controlling the thermal performance of the furnace.

The automation of the mutifactor glass-melting process implies the existence of transfer functions between the main values characterizing the quality of the glass melt and the parameters of the thermal performance of the furnace. In the ideal case we mean the formalization of the "controlled parameters of furnace performance – glass quality" relation. However, the existing methods for estimating the known glass quality parameters are not automated and do not provide a sufficient frequency of measurements to control the glass-melting process. Therefore, in practice the control of the thermal performance depends on certain arbitrary parameters, which to a certain extent determine the quality of glass. These parameters include the value and distribution of temperature in the working space of the furnace, the pressure and composition of the gaseous medium, admissible fluctuations of the glass melt level, etc. The control of these parameters is performed using local automatic systems that are not logically related to each other. Their contemporary evolution is directed to improving control algorithms, increasing the reliability of hardware components of the systems (control sensors, regulators, microprocessors, etc.), expanding the range of information services for the personnel, etc. At the same rime, the methodical basis of control systems has remained unchanged for several decades, although the design of the furnace and its operating intensity have undergone substantial modifications.

According to automatic control parameters, including temperature, a glass-melting furnace is a static object [1]. In this context the notion of "controlling the temperature regime of the furnace" understood as temperature variation in time appears incorrect. Therefore, one of the main systems of automated control of the thermal operation of a glass-melting furnace is designed to stabilize a preset temperature level and distribution inside the flame space. In furnaces with a lateral flame direction, the object of regulation can be the working space temperature in several zones whose quantity should coincide with the number of pairs of burners. In furnaces with the horseshoe-shaped flame, the object of regulation is the maximum temperature. All other control points provide information. It should be noted that the control of temperature distribution in the furnace is one of the most complicated problems in the thermal engineering of glass melting. This is due primarily to the difficulty of measuring true temperatures and a limited number of control points which do not give a sufficiently full picture of the temperature field inside the furnace, in particular, in the glass melt. Second, this is due to the significant inertia of the object of control and the mutual dependence of the temperatures in the furnace and the controlling effect, which is the fuel or electricity rate. Therefore, the control problem is solved indirectly.

Temperature in a furnace can be controlled using various methods [1 – 3], of which the most common are the stabiliza-

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tion of a preset temperature distribution over the working space by varying the fuel rate and the stabilization of the fuel rate compensating for external effects on the furnace temperature regime. In this case a preset fuel to air ratio is automatically maintained [3]. It is believed that by correctly setting the maximum temperature levels and positions one can provide conditions for an adequate technological process. Special attention is paid to the position of the temperature maximum along the furnace length, which needs to coincide with the quellpunkt of the melting tank [4 – 7].

According to the chart of the glass melt surface determined by the glass-melting process, the melting tank is arbitrarily (along the length of the zones) split into the melting zone (batch and foam) and the clarification zone (pure glass surface). The maximum temperature zone, as a rule, is oriented toward the middle of the clarification zone [5]. There are different opinions regarding the position of the temperature maximum, as applied to furnaces with a lateral flame direction: in the middle of the melting tank [6], at a distance of 2/3 of the tank length from the charging hopper [4]; near or above the spillway [7]. At the same time, the authors in [8] note that the quellpunkt position along the length of the tank is not clearly determined and does not always coincide with the temperature maximum. The position of the visual melting zone boundary is proposed as a criterion for the adequacy of a preset temperature curve and the position of its maximum. Temperature levels for the particular zones are specified based on practical data. For a furnace with the specific glass melt output over 2 tons/m^2 per day the maximum temperature can reach 1600°C [6]. Considering the service temperature constraint on the silica brick roof, the method of stabilizing temperature in the working space by varying the fuel rate appears questionable. This is especially true of contemporary highly efficient furnaces with the horseshoe-shaped flame intended for melting container glass.

The efficiency of control systems to a large extent is determined by the reliability of initial information on the state of the object of regulation. Furnace temperature is one of the most difficult control parameters. It is known that the gaseous medium in the working space of high-temperature furnaces is characterized by a nonuniform temperature field. Therefore, the “furnace temperature” notion is arbitrary, and the thermal state of the working space is usually characterized by the notion of “effective temperature.” In designing furnaces, only the average mass temperature of gases can be taken as the effective temperature, and the method for its calculation implies using known (or preset) fields of temperatures, gas velocity, concentration of combustion products, etc.

The temperature of the gaseous medium in glass-melting furnaces is measured by TPR (300 – 1600°C) and TPP (0 – 1300°C) thermocouples, as well as total or selective radiation pyrometers. Specialists know well the advantages and disadvantages of these sensors and the factors affecting the reliability of their signals. Therefore, these aspects need not be discussed now. It is interesting to estimate the methods for their installation. Thermocouples, as a rule, are installed via the furnace roof and pyrometers in the lateral walls of the working space. The protective casing of the thermocouple and the sleeve inside which the pyrometer is sighted are introduced into the gaseous medium to 50 – 100 mm [1]. In this installation scheme, the thermocouple casing and the pyrometer sleeve have complex (radiation-convection) heat exchange with the turbulent gaseous medium and the heated surfaces of the brickwork and the glass melt. In this way the signal received from the thermocouple (pyrometer) depends on many service parameters (length and shape of the flame, hydraulic regime, glass melt surface chart, etc.) and cannot be taken as an objective characteristic of the thermal state of the gaseous medium.

Despite the apparent paradox of the following statement, a substantial disadvantage of this method of installing temperature sensors is the low inertia of the object of control. To increase the stability of the regulating system, it appears useful to “roughen” to a certain extent the primary signal. This implies the choice of a more inertial object of control. Such an object can be the temperature of the inner surface of the furnace brickwork, preferably the roof temperature. Setting the temperature curve, especially its maximum based on the temperature of the inner roof surface, yields some positive results. First, a more accurate measurement of this temperature is possible by placing the thermocouple casing flush-mounted from the inner brickwork surface. Second, an objective monitoring of the maximum roof temperature is achieved, which helps to avoid emergencies related to overheating the roof. Third, the roof temperature is more inertial to short-time deviations from furnace regulations. Finally, which is the most important, under certain conditions the maximum furnace temperature correlates well with other thermotechnical and service parameters of the furnace.

In general one can state that the main problem of the temperature control algorithms used in the domestic glass-melting industry consists in the difficulty of correctly setting the temperature value and distribution and choosing representative points and control methods ensuring information that is adequate to the real thermal performance of the furnace. Similar conclusions can be derived as applied to other thermotechnical parameters (static pressure, gas medium composition etc.), which are the objects of regulation of local control systems. First, we should accept that the automation of a glass-melting furnace is impossible without creating a computer database, which is part of the central control system. The practical implementation of this approach has become possible after developing a contemporary mathematical model of a glass-melting furnace that is based on numerical modeling methods [9 – 11].

Let us illustrate the possibilities of numerical modeling for creating a database for control of the thermal performance of the glass-melting furnace. The calculation have been made for a furnace with a horseshoe-shaped flame heated by natural gas with the lowest working heat-generat-

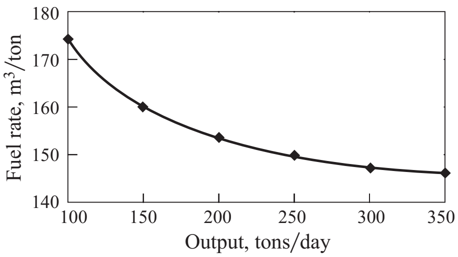

Fig. 1. Dependence of fuel rate on furnace output.

ing capacity of 35041.9 kJ/m^3 and intended for melting brown bottle glass. Other initial data, including the geometrical dimensions of the working space, melting tank, the neck, the site, and the sizes of the spillway are given in [9]. The total length of the flame is taken equal to the working space length of 13.62 m, which corresponds to the intense combustion zone (visible part of the flame) equal to 0.7 of the melting tank length. The furnace output varied within the limits of 100 – 350 tons/day. The specific glass melt output was 0.864 – 3.023 tons/m^2 per day. The averaged mass temperature of the glass melt at the entrance to the neck was taken constant and equal to 1300°C. At the same time, the variation in air temperature due to the modification of the quantity and temperature of exhaust combustion products was taken into account.

Analyzing the calculation results let us primarily consider the dependence of the fuel rate b on the furnace efficiency P (Fig. 1). This dependence quantitatively and qualitatively correlates well with the performance parameters of highly efficient glass-melting furnaces. Thus, the unit heat consumption in the considered specific output range varies in the limits of 6107 – 5119 kJ/kg (1459 – 1223 kcal/kg). The function $b = \oint(P)$ can be well described by a polynomial of the fourth degree with the mean quadratic approximation error $R^2 = 0.9999$ (m^3/ton):

$$b = 258.85 - 1.438P + 0.0077P^2 - 2 \times 10^{-5}P^3 + 2 \times 10^{-8}P^4. \quad (1)$$

The data in Fig. 2 are of interest. First, we should note that the increase in the furnace efficiency implies a substantial growth in the maximum temperatures of the roof and the glass melt surface. At $P = 100$ tons/day the maximum roof temperature $t_{\text{r.m}} = 1467.8$°C. Within this output range the maximum glass melt temperature (at the quellpunkt) grows from 1403.9 to 1500.1°C. At the same time, the growth of the furnace efficiency in percent is ahead of the required temperature increase. This determines the course of dependence (1). We can also note a certain increase in the difference between the maximum temperatures of the roof and the glass melt registered with an increased furnace output. At $P = 100$ tons/day this difference is 63.93°C and at $P = 350$ tons/day it reaches 108.7°C. The regression equations for the functions $t_{\text{r.m}} = \oint(P)$, $R^2 = 1$, and $t_{\text{g.m}} = \oint(P)$, $R^2 = 1$ have the following form:

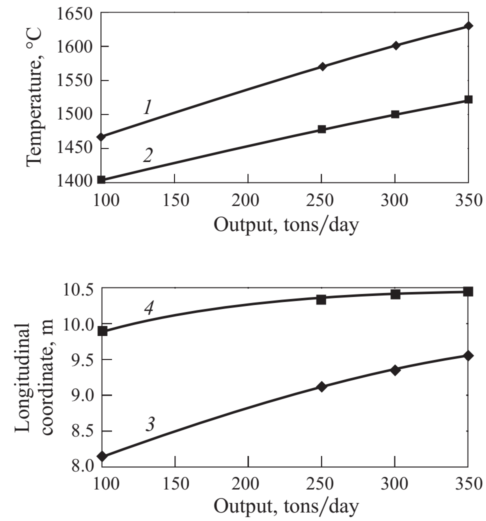

Fig. 2. Dependence of the maximum temperature on the roof (*1*) and on the glass melt surface (*2*) and their longitudinal coordinates (*3*) and (*4*), respectively, on furnace efficiency.

$$t_{\text{r.m}} = 1383.2 + 0.9317P - 0.0009P^2 + 8 \times 10^{-7}P^3;$$

$$t_{\text{g.m}} = 1344.5 + 0.6442P - 0.0005P^2 + 4 \times 10^{-7}P^3. \quad (2)$$

Equation (2) can be used to determine the limiting efficiency of the furnace that can be reached without additional electric heating, with the constraint on the service temperature of the refractories. If under changes of the furnace efficiency the average glass melt temperature at the entrance to the neck is maintained constant, the maximum temperature on the glass melt surface (i.e., the quellpunkt) is uniquely related to the maximum temperature of the furnace roof. For the specified conditions this dependence with the correlation coefficient $R^2 = 0.9965$ is described by the quadratic function:

$$t_{\text{g. m}} = 4423.9 + 4.506t_{\text{r. m}} + 0.00167t_{\text{r.m}}^2.$$

The dependences of the longitudinal coordinates (Fig. 2) of the maximum roof temperatures $X_{t_{\text{r. m}}}$ ($R^2 = 1$) and the glass melt surface (quellpunkt) $X_{t_{\text{g. m}}}$ ($R^2 = 1$) on furnace efficiency are approximated by the functions (m):

$$X_{t_{\text{r. m}}} = 1383.2 + 0.9317P - 0.0009P^2 + 8 \times 10^{-7}P^3;$$

$$X_{t_{\text{g. m}}} = 1344.5 + 0.6442P - 0.0005P^2 + 4 \times 10^{-7}P^3.$$

Evidently the position of the roof temperature maximum to a large extent is determined by the fuel combustion condi-

tions, i.e., the flame length l_f. This dependence is described by the equation ($R^2 = 1$)

$$X_{t_{\mathrm{r.\,m}}} = 13.324[1 + \exp(2.1616 - 0.3901 l_f)]^{-2.0428}.$$

The quellpunkt position depends not only on the temperature field of the glass melt surface, but also on the melting tank design, primarily on the presence of obstacles impeding a "normal" flow of the melt (air-lift system, spillway threshold, etc.) [10]. In our case this accounts for a certain discrepancy between the position of the quellpunkt and the maximum roof temperature.

To conclude, it should be noted that the specified dependences can be regarded as transfer functions in constructing an algorithm for controlling the thermal performance of the specified furnace design. Presumably the evolution of automated control systems for the thermal performance of glass-melting furnaces will involve the development of multilevel algorithms. Although the roof temperature seems attractive as an object of regulation, this parameter is not amenable to correct measuring and does not fully reflect the complexity of the processes inside the furnace. Furthermore, this parameter is not a direct characteristic of any aspect of the glass melt quality. Advances in numerical modeling methods make it possible to construct a more complex control algorithm, as well as making it more reliable and more adequate to the furnace conditions. The possibility of a combined solution of the external and internal heat exchange problem justifies the transition to controlling the thermal work of the furnace by controlling (stabilizing) the glass melt temperature, primarily at the entrance to the furnace neck.

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